MBE-Grown Devices
Room Ballroom A - Session GD-MoA1

Photonic Devices
Moderator: Prof. Dr. Minjoo Larry Lee, University of Illinois Urbana-Champaign

1:30pm **GD-MoA1-1 Separate Absorption, Charge, and Multiplication Avalanche Photodiodes With InGaAs/GaAsSb Type-II Superlattices Grown by Molecular Beam Epitaxy***, **Hyemin Jung**, S. Lee,* The Ohio State University*; X. Jin, Y. Liu,* University of Sheffield, UK*; T. Ronningen,* The ohio state university*; C. Grein,* University of Illinois at Chicago*; J. David,* University of Sheffield, UK*; S. Krishna,* The Ohio State University

Avalanche photodiodes (APDs) can be used in remote sensing applications, such as atmospheric greenhouse gas monitoring, free-space optical communications, and medical diagnostics, including the extended short-wavelength infrared (eSWIR) range between 1.3 µm and 2.5 µm. APDs have internal multiplication characteristics that allow them to detect weak signals. However, traditional p-i-n structure APDs, commonly used for longer infrared wavelengths (1.55 – 3.4 µm), can be performance-limited by the high dark currents due to band-to-band tunneling when subject to high electric fields. A separate absorption, charge, and multiplication (SACM) structure can be employed to improve their performance. The SACM structure decouples the absorption region from the multiplication regions, maintaining the absorber region below the tunneling threshold while keeping a high electric field only in the multiplier. In this work, we designed, grew, and fabricated an eSWIR SACM APD. The epitaxial layers grown by molecular beam epitaxy consist of a 5 nm-In0.53Ga0.47As/5 nm-GaAs0.51Sb0.49(InGaAs/GaAsSb) type-II superlattice (SL) absorber and 1000 nm-thick Al0.85Ga0.15AsSb (AlGaAsSb) multiplier on a InP substrate. The development of the SL involved the growth of InGaAs with a growth rate of 1 µm/hr and a V/III beam equivalent pressure (BEP) ratio of ~10, along with GaAsSb grown at a rate of 0.47 µm/hr and a V/III BEP ratio of ~20. Both were grown at a temperature of 470 °C, as measured by the Bandit system. Meanwhile, AlGaAsSb was grown at a rate of 0.6 µm/hr and a temperature of 500 °C. The X-ray diffraction (XRD) result of our devices is presented in Figure 1, which reveals a mismatch of -440 arcsec and -260 arcsec for AlGaAsSb and SL, respectively. The period of the SL was calculated from a distance between the satellite peaks, determined to be 9.75 nm. These devices have a cut-off wavelength of 2.4 µm, a gain of up to 60 at room temperature, and a resulting quantum efficiency of 600% at 2 µm. as shown in Figure 3. Furthermore, the excess noise factor of our AlGaAsSb-based SACM APD stays below 2.2, up to a gain of 30. This value is considerably lower than competing technologies, with 2 times lower than InAlAs-based SACM APD and 1.2 times lower than InAlAsSb SACM APD on GaSb at the gain of 10. These results demonstrate the potential of AlGaAsSb-based SACM APDs with InGaAs/GaAsSb SLs for various eSWIR detection applications and provide insight into the design and fabrication of SACM APDs with good noise and sensitivity characteristics, making them suitable for a range of remote sensing applications in the eSWIR range.

1:45pm **GD-MoA1-2 Growth of MWIR ICLEDs on Silicon using Molecular Beam Epitaxy***, **Mega Frost**, T. Rotter, F. Ince, G. Balakrishnan,* University of New Mexico*; M. McCartney, D. Smith,* Arizona State University*; C. Canedy, W. Bewley, S. Tomasulo, C. Kim,* U.S. Naval Research Laboratory*; M. Kim,* Jacobs Corporation*; I. Vurgaftman, J. Meyer,* U.S. Naval Research Laboratory

Previously, interband cascade light-emitting diodes (ICLEDs) grown on GaSb substrates have been demonstrated as useful emitters in the mid-wave infrared (MWIR) region of 3 – 5 µm for room-temperature (RT) continuous wave (CW) operation [1,2]. Transferring this technology to growth on Silicon substrates would be advantageous for applications in chemical sensing and IR scene projectors (IRSPs), providing improved manufacturability through direct integration onto these circuits. This presentation will discuss the comparison of high-performance ICLEDs grown at NRL on GaSb/Si buffers that were grown at UNM and on lattice-matched GaSb substrates, including L-I characteristics, cross-section transmission electron microscopy (XTEM) and x-ray reciprocal space mapping (RSM).

The growth of GaSb/Si involves GaSb buffer layers which were grown on Silicon (001) with a 4° offcut towards (111). The native oxide was removed using a dilute HF solution to obtain a hydrogen-passivated surface. To achieve III-V nucleation on Silicon, a ~10 nm thick AlSb layer was grown at a substrate temperature of 500°C followed by a 1 µm buffer layer and an antimony cap to prevent oxidation. The GaSb/Si wafers were then transferred to NRL where an additional 2-3 µm GaSb buffer and the ungrouped active ICLED stages were grown. This same 22-stage structure was grown on a GaSb substrate as a control sample. Accounting for differences in architecture, the ICLED structures grown on Silicon show efficiencies that are 75% of those measured in ICLEDs grown on GaSb. At 100 mA, 200-µm-diameter mesas produce 184 µW CW at 25°C and 140 µW at 85°C.

Threading dislocations were observed in GaSb buffer grown on Si from the XTEM images, showing a higher density near the Silicon substrate but reduced near the ICLED. Individual dislocations which reached the active ICLED layers exhibited a multiplying effect throughout the structure. Another growth artifact seen in these images was a slow-varying oscillation in the ICLED layers. Our presentation will provide a detailed explanation for both mechanisms and a comparison of the ICLEDs grown on Silicon to those grown on GaSb. Possible strategies for improving the epitaxial quality and device performance will also be discussed.

[1] C. S. Kim et al., Opt. Engr. 57, 011002 (2018).

[2] N. Schäfer et al., Opt. Engr. 58, 117106 (2019).

+ Author for correspondence: mdfrost@unm.edu [mailto:mdfrost@unm.edu]

2:00pm **GD-MoA1-3 Monlithic Integration of InAs Quantum Dot Lasers with Silicon Photonic Waveguides***, **Alec Skipper**, K. Feng,* University of California Santa Barbara*; G. Leake, J. Herman,* SUNY POLY, Albany*; C. Shang, R. Koscica,* University of California Santa Barbara*; D. Harame,* SUNY POLY, Albany*; J. Bowers,* University of California Santa Barbara

Modern silicon photonic platforms promise to drastically improve bandwidth, data rate, and power consumption in data centers while data usage is rising rapidly every year. Silicon's indirect band gap makes it impractical for use in the lasers necessary for transmitting data, requiring integration with other materials such as III-V semiconductors. Monolithic integration by growth of III-V semiconductors on silicon is a promising pathway for cost-efficient production due to the large wafer sizes and ease of packaging and testing compared to hybrid approaches utilizing separate chips [1]. However, on-chip coupling between silicon photonic waveguides and directly grown III-V lasers shows extremely high insertion losses of 7.35 dB [2], significantly reducing the chip's overall performance.

After etching a window in a patterned silicon photonics wafer, a laser stack can be grown in the opening by molecular beam epitaxy to create a chip where silicon nitride-based waveguides are aligned with InAs quantum dot active regions. Careful calibration of etch and growth rates allows good control of the vertical alignment of the active region and waveguides, but typical MBE growth conditions result in a large horizontal gap between them. While high-performance lasers have been demonstrated on 300mm silicon photonics wafers [3], this gap makes coupling challenging and needs to be addressed for monolithic integration to be competitive with hybrid and heterogeneous silicon photonic implementations.

To improve the coupling between III-V lasers and silicon photonic waveguides, growth conditions must be tailored to minimize the gap between the laser's active region and the waveguide. Polycrystalline III-V material formed on the silicon dioxide sidewall during the growth of the GaAs buffer causes the crystalline laser stack material to facet and grow away from the sidewall. By increasing the growth temperature, decreasing the growth rate, and decreasing the arsenic overpressure during the growth of the GaAs buffer, the formation of polycrystalline material is suppressed and the horizontal gap between the active region and the waveguide can be reduced from ~5 µm to ~1 µm. Active-passive coupling tests are in-progress and will be reported at the conference.

[1] Z. Zhou et al., "Prospects and applications of on-chip lasers," eLight 2023.

[2] W.-Q. Wei et al., "Monolithic integration of embedded III-V lasers on Soi," Light: Science & Applications 2023.

[3] C. Shang et al., "Electrically pumped quantum-dot lasers grown on 300 mm patterned si photonic wafers," Light: Science & Applications 2022.

2:15pm **GD-MoA1-4 Reducing Threading Dislocation Density of Pocket-Grown InAs Quantum Dot Lasers on Patterned SiO_2/Si**, ***Rosalyn Koscica**, C. Shang, K. Feng, J. Bowers,* University of California Santa Barbara

The push for scalable silicon photonics drives interest in monolithic integration of InAs quantum dot lasers on the same chip as passive waveguides. One integration method embeds silicon nitride waveguides in SiO_2 across a Si (001) wafer. The SiO_2 is patterned to form rectangular "pockets" where the III-V laser stack is grown. Pocket lasers were recently developed on 300 mm Si (001) wafers, but they have limited optical performance and thermal tolerance compared to devices grown on unpatterned "blanket" Si (001) substrate [1]. Identifying the source of this discrepancy is essential to produce blanket-level device performance within the monolithically integrated platform. One fundamental aspect is the material quality of the pocket-grown III-V epi.

Threading dislocations (TD) generated from the mismatch in III-V/Si lattice and coefficient of thermal expansion diminish laser performance and reliability. In blanket III-V on Si growth, thermal cyclic annealing (TCA) and insertion of dislocation filter layers (DFL) lowers TD density (TDD) by over two orders of magnitude compared to untreated growths [2]. In fully pocket-grown III-V epi on Si, it is impractical to apply TCA due to temperature control and uniformity challenges across a wafer surface containing mixed SiO_2, polycrystalline III-V, and epitaxial III-V regions. Pocket-grown lasers lacking TCA have TDD on the order of 10^7 cm^{-2}, suggesting TDD as a major contribution to limited performance compared to blanket-grown lasers.

Here, an annealed GaAs interlayer is inserted between the Si substrate and the patterned SiO_2 to reduce the TDD of in-pocket devices. A planar GaAs buffer is grown on a blanket GaP/Si (001) wafer and exposed to TCA before SiO_2 deposition. After SiO_2 and waveguide patterning, DFLs and the QD laser are grown inside the pockets. The modified structure retains a patterned SiO_2 device configuration while successfully reducing TD presence in pocket-grown material to mid-10^6 cm^{-2}. Lasers with continuous-wave (CW) power of 15 mW and CW lasing up to 55 °C are demonstrated and compared to equivalent lasers grown on native GaAs substrates, showing the effect of TDs. The reduced TDD platform helps separate the known performance impact of TDD presence from subtler pocket-specific thermal or geometric effects that may also differentiate the characteristics of pocket and blanket lasers. Thus, these reduced TDD pocket-grown devices lead one step closer to realizing blanket-quality lasers for monolithic integration.

[1] C. Shang, K. Feng, E. T. Hughes, et al. Light Sci Appl 11, 299 (2022).

[2] C. Shang, Y. Wan, J. Selvidge, et al. ACS Photonics 8, 2555−2566 (2021).

2:30pm **GD-MoA1-5 MBE Growth of Near-Infrared Heterojunction Phototransistors and Visible LEDs for Night Vision Applications**, ***David Montealegre**,* University of Illinois at Urbana Champaign*; Y. Song,* Yale University*; S. Lee,* University of Washington*; B. Kim, M. Kim,* University of Illinois at Urbana Champaign*; F. Xia,* Yale University*; M. Li, A. Majumdar,* University of Washington*; M. Lee,* University of Illinois at Urbana Champaign

Night-vision goggles (NVGs) based on GaAs photocathodes and vacuum-based charge multipliers are highly sensitive with a long battery life exceeding 20 hours [1]. However, the weight and length of the bulk lenses, high-voltage transformer, and fiber bundle inverter lead to neck strain and fatigue for users. Furthermore, the response of the GaAs photocathodes cuts off at 870 nm and cannot fully use the night glow spectrum extending to 1.7 µm. The DARPA ENVISION program aims to create night vision systems that combine thin and lightweight meta-lenses with a solid-state NIR upconverter to reduce the neck torque from current NVGs. In this work, we describe MBE growth of InP/InGaAs npn heterojunction phototransistors (HPTs) and AlInGaP/GaAs visible LEDs, enabling us to demonstrate upconversion of 1.55 µm light to 625 nm visible light. Rapid thermal annealing (RTA) of the LED greatly reduced the forward current needed for visible electroluminescence and promises to increase the upconversion sensitivity by ~6x. The high sensitivity and low power consumption of the devices demonstrated here are promising for next-generation night vision systems.

The HPT was grown on n-InP (001) and consisted of an n-InP:Si emitter (1.5 µm, n = 1E18 cm^{-3}), p-InGaAs:Be base (1 µm, p=5E16 cm^{-3}) and n-InGaAs:Si collector (500 nm, n = 1E18 cm^{-3}). HPTs showed responsivity of ~700-1000 A/W over a wide wavelength range of 1.25-1.65 µm and were sensitive to incident power densities as low as 12.2 nW/cm^2; high responsivity is critical, as the HPT acts as a current source to drive the LED. The LED was grown on n-GaAs (001) and consisted of a single, lattice-matched 4 nm $In_{0.48}Ga_{0.52}P$ QW with 50 nm $Al_{0.53}In_{0.47}P$ barriers emitting at 625 nm. Rapid thermal annealing at 975°C greatly improved the external quantum efficiency of the LED, enabling a strong reduction in the forward current needed to see light with the unaided eye. An HPT and LED (each on their own separate wafers) were configured in series such that the n-type emitter of the HPT was shorted to the n-type cathode of the LED, leading to clear upconversion for incident 1.55 µm laser power density as low as ~288 µW/cm^2; in the near-term, we anticipate reducing the required incident power by ~6x. In addition to improving the efficiency of the discrete components, future work will aim to realize imagers where each pixel consists of a series-connected HPT and LED, integrated through metal-metal wafer bonding.

2:45pm **GD-MoA1-6 Optically-Addressed Monolithically-Integrated Multi-band Photodetectors Using Type-II Superlattice Materials**, ***Zheng Ju**, X. Qi, A. McMinn, Y. Zhang,* Arizona State University

Multiband photodetectors and FPAs have been developed for various commercial and defense applications such as resources survey, chemical sensing, target seeking, and eye-safe imaging for autonomous automobiles. When implementing multiband photodetectors into an FPA with more than two bands, additional terminals for each pixel greatly complicate the FPA layout and device processing, decrease the fill factor, and increase the ROIC complexity.[1] It is therefore highly desirable to minimize the number of terminals so that the FPA can be integrated with off-the-shelf single-band ROICs. This talk reports the demonstration of multiband monolithically integrated optically-addressed photodetectors using GaSb and InAs/InAsSb type-II superlattices (T2SLs) to cover SWIR, MWIR, and LWIR detection range. The operating principle of the optical-addressing design is to use multiple optical biases on a stack of photodiodes (PDs) connected in series to switch detection bands. The detecting PD is the current-limiting device and determines the spectral response.

Several test structures have been grown on GaSb substrates for this study. The epitaxial growth of these samples starts with a GaSb buffer grown at 500 ℃, followed by InAs/InAsSb superlattices overgrowth at 410℃. RHEED patterns for the buffer growths on GaSb(100) show steaky 3×1 surface reconstruction, while growing InAs/InAsSb superlattice show the alternative transitions between a streaky 2×4 and a streaky 3×1. XRD results show that the MBE-grown InAs/InAsSb T2SLs as MWIR and LWIR photodetectors are perfectly strain-balanced onto GaSb, and PL measurements show that the cutoff wavelengths are 6 and 10 µm for MWIR and LWIR photodetectors, respectively. The SIMS measurements confirm that the Be (p-type dopant) and Te (n- type dopant) doping levels reach 1019 atom/cm^(-3) in both GaSb and barrier layers. Device fabrications are processed by sequentially applying top contact deposition, mesa etching, bottom contact deposition and annealing. The metal combinations of Ti/Pt/Au and Ge/Ni/Au are used for p-contacts and n-contacts, respectively. A mixture of HF, H2O2 and DI water is used for wet etching. Additionally, device performance such as dark current and spectral responsivity have been characterized and compared with the-state-of-art multiband photodetectors. More details will be reported at the conference.

[1] E. H. Steenbergen, Appl. Phys. Lett. 97, 161111-161114 (2010).

+Author for correspondence: zhengju@asu.edu

MBE-Grown Devices
Room Hall of Ideas E-J - Session GD-MoP
MBE-Grown Devices Poster Session

GD-MoP-2 Parity-Time Symmetry Single-Mode Double-Microdisk InGaAs Quantum Dot Lasers*, K. Lin, C. Xu,* ***Tsong-Sheng Lay,*** National Chung Hsing University, Taiwan

We successfully demonstrate the parity-time symmetry (PT-symmetry) single-mode lasing operationof laterally coupled double-microdisk lasers. The microdisk lasers of disk diameter = 2.85 µm are fabricated by usingMBE-grown InGaAs quantum dots as the gain medium. The gain materials of dots-in-a-well (DWELL) structures are grown on (001) n^+-GaAs substrate by molecular beam epitaxy. The wafer structure consists of a 1 µm-thick $Al_{0.5}Ga_{0.5}As$ sacrifice layer, and an active layercomprised of a stack of six InGaAs DWELLs.In spite of the lasing output of multiple whispering-gallery modes (WGMs) from the single microdisk lasers, the laterally coupled double-microdisk lasers achieve single WGM lasing under gain-loss contrast pumping condition, literally pumping only one disk for the double-microdisk. We change the air gap distance (*d*) for the coupled double-microdisk structures to change the coupling strength (*k*) between the microdisks. Under single selective pumping (gain-loss contrast) at room temperature, the laterally coupled double microdisk lasers of *d* = 150nm, and 200nm show single lasing mode at WGM m = 1,21 (λ= 1199nm). We also fabricate the double-microdisk lasers by coating the microdisks with HfO_2 to change the coupling strength *k*. Under single selective pumping, the HfO_2–coated double microdisk lasers show a single lasing mode at WGM m = 1,20 (λ= 1277nm).

GD-MoP-3 Impact Ionization Coefficients of AlxGa1-xAsSb (*x*=0 – 1) Lattice Matched to InP Substrates*,* ***Seunghyun Lee,*** The Ohio State University*; X. Jin,* University of Sheffield, UK*; H. Jung,* The Ohio State University*; J. David,* University of Sheffield, UK*; S. Krishna,* The Ohio State University

Impact ionization is a crucial process in the physics of semiconductors that influences the operation and performance of various semiconductor devices. It is utilized in avalanche photodiodes (APDs) to increase the signal-to-noise ratio, but it can also lead to avalanche breakdown in electronic devices. To ensure reliable device operation, it is vital to determine the impact ionization coefficients of electrons and holes (α and β), respectively. In this study, we present the α and β for a range of $Al_xGa_{1-x}AsSb$ compositions, covering x from 0 to 1, as determined through measurements of avalanche multiplication. Additionally, we explore the relationship between the impact ionization coefficients and the bandgap (E_g) change (Γ and X points) along with the indirect-to-direct transition. This is because the impact ionization process is influenced by the material's band structure and the E_g.

Four PIN $Al_xGa_{1-x}AsSb$ APDs with x of 0, 0.5, 0.65 and 0.85 were grown on InP using the RIBER Compact 21DZ molecular beam epitaxy, and were fabricated for electrical characterizations. The measured photocurrent spectra of the four APDs are presented in Fig. 1 (a), which illustrates that the cut-off tail moves toward lower energy as the x gradually decreases. To investigate the behavior of the E_g with various Al compositions, the $E_{g,\Gamma}$, and $E_{g,X}$ were extracted, as shown in Fig. 1 (b), and compared with the theoretical change in Eg proposed by Adachi. The discrepancy of Eg between the theory and experiment may come from the alloy disorder that can induce lower E_g than expected in the theoretical calculation. The result suggests that the cross-over should happen around x=0.5 which is similar value predicted by Adachi.

The α and β for $Al_xGa_{1-x}AsSb$ with x=0, 0.85, and 1 were plotted as a function of inverse electric field as shown in Fig. 2 (a). Fig. 2 (b) illustrates the α and β for $Al_xGa_{1-x}AsSb$ with x=0, 0.85, and 1 as a function of x at 290 kV/cm. The α remains fairly constant until x=0.85, where it jumps up at x=0, while the β gradually increases as the x decreases from 1 to 0. This suggests that the α can change abruptly at a critical x point, and a similar point may exist for the rate of change in the β, as seen in other material systems such as AlGaInP and AlGaAs on GaAs. To gain more insight, we will explore the behavior of Eg and α and β for additional x=0, 0.2, 0.4, 0.45, 0.50, 0.55, 0.65, 0.75, 0.85, and 1 in $Al_xGa_{1-x}AsSb$. Knowing these coefficients and Eg parameters will allow engineers and scientists to design and optimize the performance of optoelectronic and electronic devices.

GD-MoP-4 Superconducting Germanium for Scalable Qubit Architectures*,* ***Patrick Strohbeen****, A. Brook, J. Shabani,* Center for Quantum Information Physics, New York University

As superconducting qubit platforms mature and algorithms demand ever-increasing qubit numbers, it is becoming increasingly clear that platform scalability is an issue that must be addressed[1]. Current state-of-the-art transmon qubits simply take up too large of a footprint to reach the number of qubits required for the exciting proposed applications[1]. One proposed solution is to merge the large shunting capacitance with the non-linear Josephson inductance into a singular circuit element[2]. This “mergemon” design is similar in concept to the original superconducting qubits in this design philosophy, however the junction area is significantly larger to accommodate the large shunt capacitance desired[2]. By increasing the area of the junction however, the contribution of the superconductor-insulator interface to the overall loss of the qubit becomes much more impactful. Thus, highlighting the need for new materials discovery and development to tackle these scalability challenges in new qubit designs.

In this talk, I will discuss our work in the Shabani lab on the development of one such superconducting material system: superconducting germanium thin films. We have previously shown attainable superconductivity via MBE growth[3] and will now discuss our work in the context of developing new qubits. The growth of these covalent superconductors by MBE is highly enticing for applications in such mergemon architectures due to the natural homoepitaxial growth relationship with lower microwave loss substrates. Growth of these superconducting films and characterization of the superconducting phase in context of qubit applications will be discussed.

[1] Y-.P. Shim and C. Tahan, Nat. Commun. **5,** 4225 (2014).

[2] R. Zhao *et. al*, Phys. Rev. Applied **14,** 064006 (2020).

[3] P. J. Strohbeen *et. al*, In Preparation (2023).

GD-MoP-5 Epitaxial Growth of High-Quality Aluminum Thin Films via Mbe for the Experimental Realization of Majorana Bound States*, A. Elbaroudy, B. Khromets, E. Bergeron, T. Blaikie, Y. Shi, A. Tam, S. Sadeghi, F. Sfigakis,* ***Zbig Wasilewski****, J. Baugh,* University of Waterloo, Canada

In-situ epitaxial Al on InAs\InGaAs shallow quantum well (QW) has become a promising material platform for condensed matter systems hosting Majorana Zero Modes (MZMs) and, ultimately, topological quantum computing. This is due to the high mobility, large Landé g-factor, and strong spin-orbit interactions (SOI) of the two-dimensional electron gas (2DEG) in InAs quantum wells as well as the relatively high critical value of the in-plane magnetic field for very thin films of aluminum. It has been shown that with a sufficiently transparent Al/InGaAs interface, a proximity-induced superconducting gap in InAs approaches that of aluminum. Other benefits of Al are its large coherence length at low temperatures and its presence in III-V MBE systems; growing Al in situ produces an ultra-clean aluminum layer and a low-defect metal-semiconductor interface. However, growing a thin (~10 nm) continuous Al layer in standard MBE systems is challenging due to the high surface mobility of aluminum in a UHV environment, even at room temperature, and its tendency for 3D nucleation. In this work, we report a study of epitaxial Al thin film growth on InGaAs surface inside a standard Veeco GEN10 MBE reactor. We investigated the effect of Al deposition rate and substrate temperature on the quality of Al layers grown. Reflection High-Energy Electron Diffraction (RHEED) was performed simultaneously at four azimuths, and Band Edge Thermometry (BET) was used to monitor the substrate heating by the radiation from the Al source. Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) were used to analyze the morphology of the Al films. X-Ray Reflectivity (XRR) and critical magnetic field measurements were performed to verify the thickness and superconductivity of the continuous smooth Al layers, respectively. The results give new insights into the kinetics of Al deposition and show that with sufficiently high Al flux, at close to room substrate temperatures, 2D growth can be achieved within the first few monolayers of Al deposition. This eliminates the need for complex LN2 cooling of the substrate and paves the way for the development of high-quality superconductor-semiconductor interfaces in standard MBE systems.

GD-MoP-6 Submicron-Scale Light Emitting Diode with Efficient and Robust Red Emission*,* ***Yixin Xiao****, R. Maddakka,* University of Michigan, Ann Arbor

Light emitting diodes (LEDs) with characteristic length scales on the order of microns or less, also known as µLEDs, have been under intense investigations for their immense promise in various display and communications scenarios. Among the many material systems investigated for µLEDs, the III-nitride family possesses many desirable material properties such as comparatively low surface recombination velocities and excellent wavelength tunability. To date, however, it has remained a challenge to achieve efficient red III-nitride µLED that is robust under different operational conditions, largely due to the material synthesis difficulties in the high levels of indium incorporation in the indium gallium nitride (InGaN) active region that are required for red emission. Here, we demonstrate, for the first time, a device synthesis strategy that enables robust and efficient red-emitting µLED with device dimensions near the submicron scale. We employ selective area plasma-assisted molecular beam epitaxy as the material synthesis platform and a combination of short-period superlattice, thick n-type GaN interlayer, and a relatively thick single-segment InGaN active region as the device structure to achieve near-submicron-scale µLEDs that emits at red wavelengths (>625 nm) over two orders of magnitude of current injection levels with 3% external quantum efficiency.

GD-MoP-7 Impact of Built-in Electric Field Direction on Performance of GaN-Based Laser Diodes*, **Henryk Turski**,* Institute of High Pressure Physics PAS, Poland*; L. van Deurzen,* Cornell University*; M. Hajdel, M. Chlipala, M. Zak, G. Muziol, C. Skierbiszewski,* Institute of High Pressure Physics PAS, Poland

Nitride devices are mainly obtained along [0001] direction. That is why the internal polarization-induced electric fields in violet to green nitride light emitting diode (LED) and laser diode (LD) structures point in a direction opposite to what is desired for efficient flow of electrons and holes. This arrangement persists because of the need to have p-type layers on top of the structure to activate it and the lack of efficient structures grown along [000-1] direction.

To go around these problems one can use plasma-assisted molecular beam epitaxy (PAMBE), instead of metalorganic vapor phase epitaxy, to grow buried p-type layers and bottom tunnel junction (TJ) to invert current flow direction, with respect to the built-in polarization [1]. We also shown that p-type-down construction can be used to realize true-blue laser diodes, but obtained devices suffered from relatively high operating voltage [2].

In the present work, we report on optimization of the Ge-doping in PAMBE [3] for the growth of low resistance and high crystal quality TJs. The use of InGaN instead of GaN led to significant enhancement of Ge incorporation enabling the improvement in the operating voltage, bringing it to the similar level as for standard laser diodes without tunnel junction. This recent improvement in electrical performance of bottom TJ laser diodes opens the possibility to present the advantages of this constructions. Thanks to suppressed current overflow past the active region and the placement of p-type layers in close contact with the substrate bottom TJ laser diodes are expected to profit from lower optical losses and more efficient heat dissipation, respectively. Continues-wave operation of the cyan bottom TJ laser diodes will be presented. Comparison between p-up and bottom TJ devices will be discussed. Other device constructions built based on bottom TJ design will be shown.

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Reference

[1] H. Turski, S. Bharadwaj, H. Xing, and D. Jena, Journal of Applied Physics **125**, 203104 (2019).

[2] H. Turski *et al.*, ECS Journal of Solid State Science and Technology **9**, 015018 (2019).

[3] H. Turski *et al.*, Materials **15** (2022).

GD-MoP-8 Demonstration of a 4.32 µm Cutoff InAsSbBi nBn Photodetector, a Lattice-matched Random Alloy III-V Solution for Mid-wave Infrared Sensing*, P. Webster, J. Logan, L. Helms, P. Grant, C. Hains, R. Carrasco, A. Newell,* Air Force Research Laboratory, Space Vehicles Directorate*; **Marko S. Milosavljevic**, S. Johnson,* Arizona State University*; G. Balakrishnan,* University of New Mexico*; D. Maestas, C. Morath,* Air Force Research Laboratory, Space Vehicles Directorate

InAsSbBi *n*B*n* photodetectors are demonstrated that are lattice-matched to the underlying GaSb substrate with a 4.32 µm wavelength cutoff at 150 K; that is 0.3 µm longer than that of lattice-matched InAsSb at this temperature reflecting a 0.5% Bi mole fraction in the InAsSbBi active region. A low growth temperature was utilized to facilitate the incorporation of Bi, resulting in a minority carrier lifetime on the order of 24 ns in the InAsSbBi active region. Nevertheless, the detectors exhibits a quantum efficiency of 17% at 3.3 µm wavelength with a dark current density of 50 $\mu A/cm^2$ at 150 K and -0.4 V bias, and the strong photoresponse turn-on characteristic of a random alloy at 4.32 µm wavelength and 150 K. A shot noise-equivalent irradiance analysis indicates that these detectors' dark-current-limited noise-equivalent irradiance of 10^{12} $cm^{-2}s^{-1}$ is 2 orders of magnitude greater than the Rule 07 expectation for this cutoff, and dark-current-limited shot noise-equivalent irradiance performance transitions to photon-limited at 1.7×10^{15} photons/cm^2s. [1]

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GD-MoP-11 Zeeman Field-Induced Two-Dimensional Weyl Semimetal Phase in Cadmium Arsenide Thin Films*, **Binghao Guo**, W. Miao, V. Huang, A. Lygo,* University of California, Santa Barbara*; X. Dai,* University of Science and Technology, Hong Kong, China*; S. Stemmer,* University of California, Santa Barbara

We report a topological phase transition in MBE-grown, quantum-confined cadmium arsenide (Cd_3As_2) thin films under an in-plane Zeeman field when the Fermi level is tuned into the topological gap via an electric field. Symmetry considerations in this case predict the appearance of a two-dimensional Weyl semimetal (2D WSM), with a pair of Weyl nodes of opposite chirality at charge neutrality that are protected by space-time inversion (C_2T) symmetry. We show that the 2D WSM phase displays unique transport signatures, including saturated resistivities on the order of h/e^2 that persist over a range of in-plane magnetic fields. Moreover, applying a small out-of-plane magnetic field, while keeping the in-plane field within the stability range of the 2D WSM phase, gives rise to a well-developed odd integer quantum Hall effect, characteristic of degenerate, massive Weyl fermions. A minimal four-band $k\cdot p$ model of Cd_3As_2, which incorporates first-principles effective g factors, qualitatively explains our findings.

Reference: B. Guo … S. Stemmer, *Phys. Rev. Lett.* 131, 046601 (2023)

GD-MoP-12 MBE Grown InAs/GaAs Quantum Dot Columns as a Buffer Layer for Spatial and Spectral Homogeneity*, **Nazifa Tasnim Arony**, L. McCabe, J. Zide,* University of Delaware

MBE grown InAs quantum dots (QDs) on GaAs substrates have been widely studied[1] because of their wide range of applications in complex quantum devices including quantum sensors and quantum computers, since the QDs can serve as a basis for potential qubits[2]. Advanced quantum devices require spatial, spectral, compositional and structural homogeneity and scalability in the grown quantum dots that must have definitive locations in an array on the substrate. Non-templated self-assembled MBE grown QDs are not a feasible option in this regard due to their spatial and spectral randomness. There is ongoing research being conducted on effective methods to overcome the current challenges of producing defect-free, homogeneous and scalable QD platforms[3]. Recent work[4] has been done by our group on low-density site-controlled MBE grown InAs QDs on GaAs platform using nano-fabricated arrays of nano pits. However, achieving spectral homogeneity and thus, scalability is still a challenge because of the impurities introduced in the regrowth surface from the nanofabrication steps. Hence, we are exploring the domain of quantum dot columns (QDCs) as a buffer layer for the top QD-arrays of interest. In this process, the spatial homogeneity can be maintained by the templated QDs in the bottom layers while burying defects underneath the QDCs and potentially, scalable platforms for devices can be achieved.

MBE-Grown Devices
Room Ballroom A - Session GD-TuA1

Solar Cell and Quantum Computing

Moderator: Prof. Dr. Minjoo Larry Lee, University of Illinois Urbana-Champaign

1:30pm **GD-TuA1-1 InSb-Based Dilute-Bismide Alloys Towards Long-Wave Infrared Sensing**, ***Corey White****, M. Bergthold, T. Leonard, A. Ricks, D. Wasserman, S. Bank,* The University of Texas at Austin

It is well-established that bismuth incorporation into III-V alloys produces a significant reduction in bandgap energy[1, 2] that can be advantageously leveraged for optoelectronic devices operating at extended wavelengths. For accessing the long-wave infrared, InSb is a particularly promising candidate host alloy due to both its narrow bandgap energy and the relatively similar ideal growth conditions for InSb and III-Bi materials. Here we report progress towards achieving wavelength extension from InSbBi with photoluminescence (PL) from InSbBi with the highest substitutional bismuth concentrations yet reported as well as methods for post-growth bismuth droplet removal.

Epitaxial InSbBi films were grown by solid-source MBE on InSb substrates. Low substrate temperatures, Sb/In flux ratios near stoichiometry, and fast growth rates were employed to encourage significant bismuth incorporation. From these films, X-ray diffraction and Rutherford backscattering spectrometry measurements were used to confirm the bismuth concentration in the films and extrapolate the InBi lattice parameter, which was found to be ~6.63 Å. This is in line with previous reports of the InBi lattice parameter[3-5] confirming that the incorporation of bismuth into InSb causes the lattice to expand. PL measurements from the InSbBi films demonstrated significant wavelength extension beyond that of InSb with emission out to ~6.5 µm at 83 K. Atomic force microscopy surface morphology measurements revealed that the samples exhibited droplet formation.

As is typically observed for dilute-bismide alloys,[3, 6] it is increasingly challenging to achieve droplet-free InSbBi surfaces at elevated bismuth concentrations. We investigated post-processing techniques for droplet removal as an alternative to attempting to completely mitigating droplet formation during growth. HCl/H_2O_2 digital wet etching, physical polishing, and ion milling were performed on a film with large bismuth droplets resulting in improvements in roughness of 2.2×, 3.7×, and 4.0×, respectively. Studies on the effects of these techniques on InSbBi optical quality are underway and will be reported at the conference.

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This work was performed at the UT Austin MRC, a member of the NNCI (NSF No. ECCS-1542159) and supported by Lockheed Martin, NSF (ECCS-1933836), and an NSF GRF (RCW). RBS measurements were performed at Rutgers LSM.

1:45pm **GD-TuA1-2 Abrupt Te Doping of MBE-Grown GaInP for Solar Cell Applications**, ***Brian Li****, Y. Sun, R. Hool, M. Lee,* University of Illinois, Urbana-Champaign

For III-V multi-junction solar cells (MJSC), 1.9 eV $Ga_{0.51}In_{0.49}P$ (hereafter GaInP) is a primary material for the high-bandgap top cell [1]. In recent years, GaInP solar cells grown by molecular beam epitaxy (MBE) have achieved high efficiencies after post-growth rapid thermal annealing (RTA) [2] similar to cells grown by metalorganic chemical vapor deposition (MOCVD). Another avenue to improve MBE-grown GaInP cells is the use of group VI dopants (Se, Te) instead of group IV dopants such as Si. For example, MOCVD-grown AlGaAs and AlGaInP cells reported superior internal quantum efficiency (IQE) by changing the dopant from Si to Se [3], [4], an improvement that correlates with the shallower defect energy levels of Se [5], [6]. MBE-grown phosphide cells may also be improved by the use of a group VI dopant, but such studies have not been reported. In this work, we show improved IQE of GaInP solar cells with Te doping of the n-type emitter over Si, which was modeled to show improved carrier lifetime in n-GaInP:Te.

A well reported issue for MOCVD GaInP:Te is undesirable Te surface segregation [7], so we first optimized MBE growth conditions to minimize segregation. GaInP samples were grown at different target concentrations of [Te] = $5.7*10^{17}$ to $1.7*10^{18}$ cm^{-3}, and doping profiles from secondary ion mass spectrometry (SIMS) indeed showed high Te surface segregation at the nominal substrate growth temperature T_{sub} = 460 °C. For example, the doping profile for target [Te] = $1.7*10^{18}$ cm^{-3}ranged by orders of magnitude ($5*10^{16}$ cm^{-3} at the start of growth to $7*10^{19}$ cm^{-3} at the surface). Next, reducing T_{sub} from 460 °C to 420 °C greatly suppressed surface segregation for all samples. Abrupt doping profiles were obtained for target [Te] = $5.7*10^{17}$ cm^{-3} solely by this reduced $T_{sub,}$ while [Te] = $1.7*10^{18}$ cm^{-3} also required a Te "pre-dose" or deposition prior to GaInP growth to achieve an abrupt doping profile. The cause of this difference in pre-dose requirement as a function of doping will be the subject of future work.

Lastly, n-on-p front junction GaInP cells were grown with both GaInP:Te and GaInP:Si n-type emitters (n > $1*10^{18}$ cm^{-3}). For as-grown cells, the IQE of the GaInP:Te cell was significantly higher than that of GaInP:Si, with the short-circuit current density derived from IQE increasing from 13.2 mA/cm^2 to 14.1 mA/cm^2. Modeling of the IQE indicates a ~4x higher carrier lifetime of GaInP:Te than GaInP:Si. This work shows the promise of GaInP:Te for improved optical material quality, and future work will explore GaInP:Te for rear-junction cells with n = 1–$5*10^{17}$ cm^{-3}, as well as the effect of RTA on GaInP:Te.

2:00pm **GD-TuA1-3 MBE Growth of Metamorphic 1 eV InGaAs Solar Cells with Low Threading Dislocation Density**, ***Adrian Birge****, M. Kim, B. Kim, D. Montealegre, M. Lee,* University of Illinois at Urbana-Champaign, USA

Growth of metamorphic (MM) $In_xGa_{1-x}As$ enables optoelectronic devices, such as near-infrared photovoltaics, detectors, and lasers with bandgap energies (E_g) ranging from 0.8-1.3 eV, to be integrated on GaAs substrates. Most previously reported MM $In_xGa_{1-x}As$ structures with x=0.3 (E_g=1.0 eV) have used metal-organic chemical vapor deposition (MOCVD) at substrate temperatures (T_{sub}) over 700°C to facilitate high dislocation glide velocity and thus low threading dislocation density (TDD)[1], while thermodynamically suppressing phase separation. MBE growth of MM $In_xGa_{1-x}As$ cannot be done at such high T_{sub} due to excessive In desorption. Thus, the MBE growth window must be chosen carefully to balance the need for adequate dislocation glide velocity while kinetically suppressing phase separation. In this work, we describe a two-step method for fully relaxed $In_{0.3}Ga_{0.7}As$ with a TDD = ~$7x10^5$ cm^{-2}, comparable to the lowest reported values for this material. On this platform we fabricated the first MM 1.0 eV $In_{0.3}Ga_{0.7}As$ solar cells grown via MBE to our knowledge.

$In_xGa_{1-x}As$ (x=0-0.3) buffers showed strong phase separation in electron channeling contrast imaging (ECCI) when all growth was carried out at T_{sub}=500°C. Therefore, we adopted a two-step approach where $In_xGa_{1-x}As$ (x=0-0.18) was grown at T_{sub}=500°C to facilitate dislocation glide[2], followed by 460°C for x=0.18-0.3 to prevent PS[3]; an $In_{0.35}Ga_{0.65}As$ overshoot layer was also included to facilitate strain relaxation. ECCI yielded a TDD < $1x10^6$ cm^{-3} without PS, while reciprocal space mapping showed 97.9% relaxation in the $In_{0.3}Ga_{0.7}As$ cap.

Using our two-step $In_xGa_{1-x}As$ graded buffer as a virtual substrate, a 1 eV InGaAs solar cell was grown and devices were fabricated both as-grown (AG) and with rapid thermal annealing (RTA)[4]. Internal quantum efficiency (IQE) measurements showed improved minority electron diffusion length in the base of the RTA cell, resulting in a 1.15x increase in short-circuit current density (J_{SC}). Lighted current-voltage (LIV) curves showed a strong improvement in the open-circuit voltage (V_{OC}) after RTA, with a bandgap-V_{OC} offset (W_{OC}) of 0.46 V, ~0.1 V higher than the best cells in the literature grown by MOCVD at NREL[5]. The fill factor (FF) and cell efficiency (η) of our RTA'd cells were hampered by high contact resistance, which will be addressed in future runs. Nonetheless, the J_{SC} (29.96 mA/cm^2) and V_{OC} (0.538 V) values of our RTA'd cells compare favorably with the best lattice-matched 1.0 eV solar cells (e.g. InGaAsN on GaAs, InGaAsP on InP) grown by MBE[6], presenting a promising path for MBE-grown MM 1.0 eV $In_{0.3}Ga_{0.7}As$ solar cells.

2:15pm **GD-TuA1-4 Strained Superlattice InAlGaAs/AlGaAs Spin-Polarized Photocathodes Implemented with Random and Digital Alloying**, ***Aaron Engel****,* University of California, Santa Barbara*; M. Stutzman,* Thomas Jefferson National Accelerator Facility*; J. Dong,* University of California, Santa Barbara*; C. Palmstrøm,* University of California, Santa Barabara

Spin-polarized electron beams are a crucial tool in particle physics experiments and specialized characterization techniques. Their production involves exciting a III-V semiconductor (the photocathode) with near-bandgap circularly polarized light. Spin-polarized photoelectrons are produced through optical selection rules. These photoelectrons are then extracted after functionalizing the surface to create a negative electron affinity condition. Increasing the electron spin polarization (ESP) and the quantum efficiency (QE) of the photocathodes enhances overall experimental efficiency, extends the photocathode lifetime, and enables the production of high bunch charge beams. The current state-of-the-art spin-polarized photocathodes consist of $GaAs/GaAs_{0.67}P_{0.33}$ strained superlattice quantum wells grown on metamorphic $GaAs_{0.67}P_{0.33}$ virtual substrates on GaAs(001), which consistently produce QE over 1% and ESP around 85%.

While the GaAs/GaAsP system is mature, it still faces many limitations. Growth of the relaxed virtual substrate results in a higher density of threading dislocations than there would be in a fully pseudomorphic system, thereby limiting QE, ESP, and photocathode lifetime. In addition, since the As/P ratio in the virtual substrate controls the lattice constants, band offsets, and band gaps, it is difficult--if not impossible--to design a stack that optimizes each of these parameters simultaneously.

Here we demonstrate fully pseudomorphic spin-polarized photocathodes based on the InAlGaAs/AlGaAs system grown by molecular beam epitaxy. By switching to this quaternary well/ternary barrier system, we may more independently optimize the strain, superlattice bandgap, and band offsets. Furthermore, control of Group III alloy composition should be more precise, reproducible, and uniform than control of Group V alloy composition. The fully pseudomorphic stack simplifies growth and reduces the dislocation density in the active region. Unfortunately, the transition from a binary/ternary system to a quaternary/ternary system will increase the random alloy disorder in the photocathode. This random alloy disorder can then cause significant reductions in ESP. To solve this, we investigate using a digital alloy for the well and/or barrier in the superlattice. Our first test structure using a random alloy photocathode design yielded polarization over 80%, but a QE of only about 0.3%. We will report on further optimization of the growth conditions of both random and digital alloy photocathodes. In addition, we will discuss the changes to the QE and ESP of the photocathodes between the two alloy schemes.

2:30pm **GD-TuA1-5 Molecular Beam Epitaxy Growth and Characterization of InAs Quantum Wells Grown on Metamorphic III-V Buffer Layers**, *I. Levy, **Patrick Strohbeen**, W. Strickland, M. Hatefipour, J. Issokson, L. Baker,* New York University*; M. Mikalsen,* new york University*; S. Farzaneh, J. Shabani,* New York University

Heterostructures of a 2-dimensional electron gas (2DEG) semiconductor and a superconductor are prime candidates for various applications including quantum computing and topological superconducting circuits [1,2]. The 2DEG layer needs to be in close proximity to the superconductor, within the structure, and to form an Ohmic contact. Heterostructure of containing a quantum well (QW) of InAs (InGaAs/InAs/InGaAs) that have a narrow bandgap with the Fermi level close to the conduction band as a 2DEG semiconductor and thin epitaxial Al layer grown on it as a superconductor. This heterostructure makes a prime candidate due to the high mobility in the 2DEG and the compatibility between the QW and the epitaxial Al.

In this work, we present our study of the growth of these heterostructures (InAs QW/Al) grown by molecular beam epitaxy [3]. We show the effect of modification of the growth conditions on the heterostructures and analyze the disorder in the samples using different techniques. Various impurities including background impurity, surface impurities, alloy scattering and surface roughness can be moderated as a function of the growth conditions. We find samples that have high indium content in their graded buffer layer show a decrease in surface roughness with growth temperature. In addition, anisotropy along rapid diffusion directions during the growth results in anisotropy in the resulting carrier mobilities parallel with these directions. We also analyze the typical cross hatch pattern of the surface on the InAs heterostructures as a function of growth parameters and relate the strain state anisotropy (or lack thereof) to the observed electrical characteristics. Lastly, we show that growth of a thin capping layer of 1 - 6 nm of $In_{0.81}Al_{0.19}As$ modifies the surface scattering on the quantum well, the implications of which will be discussed.

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2:45pm **GD-TuA1-6 Cryogenic Growth of Superconducting Thin Films on GaAs, Si, and Sapphire Substrates**, ***Teun van Schijndel**, A. Engel,* University of California Santa Barbara*; J. Dong,* University of California at Santa Barbara*; A. McFadden,* NIST-Boulder*; C. Palmstrøm,* University of California Santa Barbara

Superconducting thin films are crucial in various fields of quantum information technology, including superconducting qubits and topological quantum computing. The vast majority of either of these qubit technologies use aluminum as the superconducting component. Al is generally grown at low temperatures to achieve smooth thin films. This allows for easy integration of Al-based devices with material systems such as sapphire, Si, Ge, or III-V materials due to minimal interfacial reactions.

While aluminum is the most common, other superconductors show promising results as well. In particular, Ta- and Nb-based superconducting qubits on sapphire show low loss and long coherence times.[1,2] Due to its resilience to high temperatures, low-loss sapphire can withstand the growth of Ta and Nb at elevated temperatures necessary for the realization of desirable superconducting properties. These superconductors could be interesting for topological qubits as well, but integration of these refractory metals on high-purity semiconducting substrates with high spin-orbit coupling remains a challenge due to interfacial compound formation at higher temperatures. In fact, this can lead to additional roughness and consequently degradation of superconducting properties such as T_c.

In this work, we explore the MBE growth of superconducting thin films at ultralow temperatures below 10K (LT). In particular, we focus on the growth of refractory metals such as Ta, Nb, and V. Through a comparative study of thin film growth at ultralow temperature and room temperature (RT), significant changes in the properties of the superconducting thin films are observed. Initial experiments on SiO2/Si surfaces indicate a notable improvement in film smoothness with lower temperature growth measured by Atomic Force Microscopy. Furthermore, four-probe resistance measurements demonstrate a significant increase in the superconducting Tc for all superconductors studied. Most dramatically, we found that 20 nm Ta grown at RT did not exhibit a superconducting transition above 2K, while LT growth of Ta resulted in a superconducting film with a Tc of 3.95K. We will further investigate this behavior on GaAs(001), Si(001), and Al_2O_3(0001) surfaces and extend our study to superconductors such as Pb, Sn, and Al. Our work demonstrates the growth of high-quality superconducting thin films with ultralow temperature growth, which enables the exploration of different substrate and superconductor combinations for use in quantum information technology.

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2) npj Quantum Inf 8, 3 (2022).

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